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# DESIGN OF LIGHT-GAS MODEL LAUNCHERS FOR HYPERVELOCITY RESEARCH

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**ARNOLD ENGINEERING DEVELOPMENT CENTER**

**AIR FORCE SYSTEMS COMMAND**

**UNITED STATES AIR FORCE**

AEDC-TDR-62-97

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## ABSTRACT

The parameters which influence the operating capabilities of two-stage, light-gas guns are discussed. Calculations are presented which illustrate the relationships of these parameters under idealized conditions, and empirical correlations derived from firings in several launchers are used to provide the necessary correction factors to adjust the idealized treatment.

The construction techniques which are used in the design of light-piston-type, two-stage, hypervelocity launchers are discussed. This includes the mechanical design of development-size equipment and larger equipment for use in an aerodynamic test facility. Design features which are discussed include: (1) powder-helium or powder-hydrogen piston propulsion, (2) pump-tube, gas-heating system, (3) high pressure equipment design, and (4) maintenance equipment required for efficient operation.

## CONTENTS



## ILLUSTRATIONS

## NOMENCLATURE

| | |
|---|---|
| $A_\ell$ | Area of launch tube |
| $A_p$ | Area of pump tube |
| $a_c$ | Acoustic speed in combustion chamber after firing |
| $a_f$ | Acoustic speed after compression |
| $a_p$ | Acoustic speed in pump tube before compression |
| $d_\ell$ | Launch tube diameter |
| $d_p$ | Pump tube diameter |
| $\ell_i$ | Launch tube length |
| $\ell_p$ | Pump tube length |
| $m_\ell$ | Projectile mass |
| $m_p$ | Piston mass |
| $p_c$ | Gas pressure in combustion chamber after firing |
| $p_{c_1}$ | Gas pressure in combustion chamber before firing |
| $p_f$ | Pressure after compression |
| $p_p$ | Pump tube initial pressure |
| $\bar{s}$ | Dimensionless distance |
| $T_f$ | Pump tube final temperature |
| $T_p$ | Pump tube initial temperature |
| $\bar{u}$ | Dimensionless velocity |
| $u_i$ | Ideal launch velocity |
| $u_\ell$ | Launch velocity |
| $u_p$ | Piston velocity |
| $u_t$ | Thermodynamic launch velocity |
| $\gamma$ | Ratio of specific heats |

# 1.0 INTRODUCTION

A 1000-ft, hypervelocity, aerodynamic range (Fig. 1) is under construction at the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), USAF, and as part of the program it was necessary to design a large launcher. To provide information for this design, an analytical and experimental program has been conducted over the past two years. Early work was directed toward the use of arc-heated gas for propelling the projectile; however, gas contamination from the arc process was such a serious problem, with no readily apparent solution, that the use of arc-heating was dropped in favor of compression heating (Ref. 1). Other groups had been working with the two-stage type of light-gas gun (Ref. 2), and it was decided to modify some available equipment to use as a two-stage gun.

Very little analytical work was available to make rational decisions on gun design, and it was necessary to formulate a procedure which could predict gun performance. The first part of this report describes the calculation procedure which was developed. The experimental program which was carried on served to provide empirical corrections to the analysis, as well as the development of mechanical design criteria and operating techniques which were best suited to this type of gun. Some of these developments are given in the second part of the report.

# 2.0 PERFORMANCE ANALYSIS

The performance analysis of the gun can be conveniently broken down into three operations: (1) calculation or measurement of the piston velocity, (2) the compression process by the piston in the pump tube, and (3) the launching of the projectile by the compressed gas. The calculation procedure and its ramifications are given in some detail in Refs. 3 and 4, with general results being given here.

## 2.1 PISTON VELOCITIES

A large amount of the piston velocity information of an empirical nature has been obtained with several modes of first stage operation being employed. The first method was the $3H_2$-$O_2$-8He combustion system.

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This type of operation has been defined in Ref. 5, and generalized curves have been prepared which give the piston velocity over a wide range of gun parameters. The curves of piston velocity are given in Fig. 2a with hydrogen and helium in the pump tube.

For larger guns it is difficult to obtain satisfactory ignition of the $H_2$-$O_2$ mixture without serious detonation, and for this reason, it is desirable to operate with smokeless powder supplying the energy. Operation using powder-driven pistons has been investigated in some of our small guns used for launching impact models. This work was discussed in Ref. 6, and the summary of piston velocities obtained in this work is given in Fig. 2b.

It is possible to obtain piston velocities above those which can be obtained by direct powder driving by the use of helium or hydrogen in a larger powder chamber. The powder is placed in the uprange end of the chamber and heats the hydrogen or helium by compression, which then propels the piston down the pump tube. Some shots were fired using different types of powder to try to determine the type of powder which is best suited for this type of operation. The chamber which was used in these tests was 4.25 inches in diameter and 90 inches long. Ignition was accomplished by a Mark 27 torpedo primer mounted in the breech plug. It appeared that a medium-fast IMR-type powder gave maximum piston velocity for the same chamber pressure. Slower burning powders (IMR 7005, etc.) seem to mix with the gas to such an extent that lower sonic velocity is obtained. With higher burning rate powder (IMR 4227) there was a high pressure spike generated in the downrange end of the chamber, which damaged the chamber when sufficient powder was used to obtain the same velocity which could be achieved with slower burning powder. IMR 4198 and 4895 were used to obtain the data shown in Fig. 2c. The use of hydrogen with the powder created no noticeable difficulties; in fact, the gun operation was cleaner than when using helium.

## 2.2 PUMP TUBE CONDITIONS

Once the piston velocity has been determined, the conditions in the pump tube can be calculated using some basic assumptions. These assumptions, using Fig. 3 as a reference, are briefly: (1) the piston achieves a constant velocity near the end of the pump tube, and the gas in front of the piston has uniform properties; (2) the shock in front of the piston reflects from the downrange end of the pump tube and travels back to the piston, leaving the gas in the pump tube at rest at this time;

(3) the kinetic energy of the piston is then added to the internal energy of the rest gas to arrive at the final state of the compressed gas; and (4) the final entropy of the gas is determined from the entropy after the shock reflects from the piston face, assuming an isentropic compression from this state. Under these assumptions, it is found that the four parameters needed to express pump tube performance are: (1) piston speed, $u_p$; (2) pump tube initial pressure, $p_p$; (3) pump tube initial temperature, $T_p$; and (4) a piston mass parameter, $\frac{m_p}{A_p \ell_p}$. If, as is the usual practice, the final pressure at the end of the compression process is limited for structural reasons, the final state of the compression process can be determined as shown in Fig. 4. The final acoustic speed and final volume are given as functions of the piston velocity and mass for a given initial temperature of 300°K. It should be noted that increasing piston velocities or piston mass results in lowering of the acoustic speed and an increase in final volume. Since the launch velocity is influenced by these quantities and their trends are of opposite slope, it can be expected that definite maxima in launch velocity can occur when the pump tube parameters are varied.

## 2.3 LAUNCH PERFORMANCE

The calculation of the launch velocity proceeds along established methods by first calculating the projectile velocity, assuming that the propellant has the final state as established above and the chamber is the same diameter as the launch tube and of infinite length. This solution is available in closed form

$$\bar{s} = \frac{2}{\gamma - 1}\left[\frac{\frac{2}{\gamma + 1} - \left(1 - \frac{\gamma - 1}{2}\bar{u}\right)}{\left(1 - \frac{\gamma - 1}{2}\bar{u}\right)^{\frac{\gamma + 1}{\gamma - 1}}} + \frac{\gamma - 1}{\gamma + 1}\right]$$

$$\bar{u} = \frac{u_t}{a_f} \qquad \bar{s} = \frac{p_f A_\ell \ell_\ell}{m_\ell a_f^2}$$

and by suitably correcting this velocity by the method of Ref. 3 for the effect of finite chamber volume (Fig. 5), the final launch velocity can be predicted. The results of such a calculation for a typical case are given in Fig. 6a. This calculation is made for gun-shooting a one-caliber slug having a specific gravity of 1.20, using a 200-caliber launch tube, and a maximum pressure of 20,000 atm of hydrogen. Matching the piston velocity information given earlier then allows the calculation of the entire gun performance.

## 3.0 EMPIRICAL CORRECTIONS

The type of two-stage guns which have been fired to obtain these data had piston velocities between 3000 and 8000 ft/sec and used relatively light pistons compared to some two-stage guns. The pistons were of plastic and from 0.75 to 1.5 calibers in length. The firings reported in Ref. 2 and firings at AEDC were correlated to provide corrections to the calculated velocity (Ref. 1). These firings covered a wide range of operating conditions and gun parameters. Three parameters could be defined which reduced the actual velocity below the theoretical velocity. They were: (1) $\frac{m_p}{m_\ell}\frac{A_\ell}{A_p}$, termed the piston reversal parameter, which places a lower limit on piston weight to be used in a given configuration; (2) $\Delta s/d_\ell$, which is the movement of the projectile under the influence of the first reflected shock until final conditions are reached; and (3) a temperature correction term based on the final temperature reached in the compression process.

The relation which was fitted to the data was:

$$u_\ell/u_i = 1 - \left(\frac{0.4}{\frac{m_p}{m_\ell}\frac{A_\ell}{A_p}}\right)^2 - 0.9 \times 10^{-6}\left(\frac{\Delta s}{d_\ell}\right)^3 - 3\,(T_f - 2000°K) \times 10^{-5}$$

Using this correction and the previously calculated ideal launch velocity, the performance of this type of two-stage gun can be calculated. When the corrections are applied to Fig. 6a, then the results shown in Fig. 6b are obtained.

## 4.0 PERFORMANCE WITH HEATED PUMP TUBE GAS

As part of a program to improve gun performance, a study was made to determine whether the use of preheated gas in the pump tube prior to compression would increase the launcher's performance level enough to be worthwhile. A heating system was required that would not deteriorate the plastic pistons and projectiles nor affect the strength of the high pressure section. Preliminary estimates indicated that with a 300,000-psi final pressure behind the projectile, the velocity increase would amount to 3000 ft/sec when the propellant is hydrogen-heated to 600°K. An experimental program was conducted using the steam-heated, 40-mm gun for the first stage coupled to a 0.5-inch launch tube as the second stage. Using the piston velocities and calculation method outlined, the effect of preheating the pump tube gas was estimated. Figure 7 is a plot of corrected launch velocity vs final pressure for pump tube temperatures of

300 and 600°K. This plot is for the specific set of gun conditions noted on the figure with lines of constant pump tube pressure as a parameter.

Several methods of heating the pump tube gas were considered, and some preliminary experiments were conducted on different equipment for obtaining the desired conditions (i. e., 600°K $H_2$ up to 600 psi). It was decided to try a flow-type system which could reach relatively stable conditions in a short period of time (approximately 10 sec or less).

Figure 8 is a schematic of the heater system as it was finally used. The hydrogen is stored in the bottles shown in the lower right of the picture and feeds into a manifold and through a regulator, which is set to reduce the pressure from bottle pressure to approximately 50 psi above the final pressure desired in the pump tube. After passing the inlet valve, the flow is then divided and goes to the two heater coils. The heaters consist of one-inch OD, 0. 625-in. ID, stainless steel tubing coiled and placed in insulating containers. Cables are clamped on each end of the coil, and power is supplied from transformers with each heater drawing 900 amp at 45 volts a-c. The heated gas then flows through a check valve and into the pump tube. The temperature of the gas in the pump tube is measured by a thermocouple mounted so that it can be retracted out of the path of the piston just before the gun is fired. A transducer records the pressure in the pump tube, and the pressure is also monitored visually by means of a pressure gage and a television camera. A small valve isolates the transducer from the high pressure in the pump tube at the instant of firing. A pressure switch prevents the gun from firing if the pump tube pressure is less than specified, since any last second failure which lowered the pump tube pressure could cause enormous pressures in the high pressure section.

The gas flows out at the midpoint of the pump tube through the main exit valve. This valve is gas-operated so it can be opened and closed, but it functions also as a check valve during the firing. The exit temperature is monitored by a thermocouple mounted immediately downstream of the exit valve. Two diaphragm-actuated valves are mounted in parallel and are used as flow control valves. They are controlled by individual regulators on the control panel. One is preset to a specified position, and the other one is manually operated to adjust the pressure in the pump tube during the few seconds of gas flow preceding the shot. From the control valves the gas is vented to atmosphere outside the building. Figure 9 is a photograph showing the equipment in place.

The usual method of operation is to turn on the power and let the heaters warm up for a length of time determined by the gas temperature

desired. For 600°K pump tube temperature, this is approximately one min, 45 sec before firing. At approximately one min before firing, the inlet valve is opened, and with the exit valve closed, the pressure in the pump tube stabilizes at a pressure approximately 50 psi above the desired firing pressure. The flow control valves have been preset so that when the exit valve is opened, the pressure in the pump tube will drop to the firing pressure. At 15 sec before firing, a short burst of approximately one-sec duration is run through to check the settings of the flow control valves and make adjustment, if necessary. The pressure is monitored by means of the gage on the pump tube and a television receiver in the control room. At 5 sec before firing, the exit valve is again opened, and gas flows through the pump tube at a rate of approximately 5 to 7 lb of hydrogen per min. The pressure is continuously monitored and adjusted by means of one of the flow control valves, if necessary. Flow continues until the gun fires, with the check valves preventing the loss of gas. The system is capable of pressures up to 1000 psi, but normal operation is in the 400 to 700-psi range. Inlet temperatures up to 1500°K can be obtained, but normally they are from 900 to 1200°K. The pump tube temperatures are normally from 300 to 750°K.

Several hardware items were developed during this program which led to successful operation of the system described above. The heaters are essentially storage-type heaters which could provide outlet temperatures up to 1500°K without contamination of the gas flowing through them. Figure 10 is a sketch of the heater showing major components. One of the continuing problems encountered was contamination of the pump tube charge with the consequent lowering of acoustic velocity and, hence, launch velocity. These heaters, in conjunction with the continuous-flow system which carried away impurities which were generated, served to provide clean gas at the time the compression process took place. The check valves are high-flow, quick-acting checks which can withstand 50,000-psi operating pressures after flowing the high temperature gas. The exit valve has a 0.75-inch port and can stand at least 30,000 psi. The valve, as built, will open and close in 50 milliseconds at the pump tube charge pressure, yet will withstand the high pressure encountered during a shot.

Typical results which were obtained with the system are shown in Fig. 11. The flow of gas was started 5 sec before fire, as evidenced by the rapid rise in inlet temperature. The system stabilized fairly rapidly with plenty of time to make pressure adjustment if it had been necessary. The time involved is rather short, and for consistent results over a wide range of operational settings, an automatic system would have been useful.

Figure 12 is a plot of the temperature profile of the hydrogen flowing in the pump tube, as obtained with the already mentioned retractable thermocouple. It is seen that the mean temperature is about 97 percent of the temperature at the center of flow. This particular shot had a velocity of 29,600 ft/sec with a one-gram Lexan projectile.

The experimental velocities obtained with the heating system in operation are presented in Fig. 13. The heated shots were at approximately 600°K average temperature in the pump tube and the cold shots at 300°K. The format is the same as the calculations given in Fig. 7; however, in this case, the final pressure was calculated from measured pressures in the combustion chamber rather than the 20,000 psi assumed in the earlier figure. The average increase in performance at the same final pressure is 10 percent.

## 5.0 CONSTRUCTION AND OPERATING TECHNIQUES FOR TWO-STAGE GUNS

In order to facilitate testing with two-stage guns, some construction techniques, operating limits, and operational methods have been developed; some of them are discussed here.

### 5.1 HIGH PRESSURE SECTION DESIGN

To achieve high velocities, it is necessary that quite high pressures (over 200,000 psi) be contained in the high pressure section and initial portion of the launch tube. In the course of the experimental program it was found that during the firings, the ID of the high pressure section would grow. Figure 14 shows some of the measured diameters during a series of shots, using a 6-inch OD high pressure section. However, the performance of the gun did not seem to deteriorate while the ID of the nominally 1.58-inch-diameter section had grown above 1.75 inches in diameter, the piston apparently swelling and filling the increased diameter. This, then, indicated that the high pressure sections could be used to the full overstrain pressure (the pressure at which plastic flow reaches the outer wall) and perhaps even beyond.

The curves of Fig. 15 indicate the relative magnitude of the pressures which can be contained by purely elastic behavior, and by allowing the plastic flow to progress to the outer wall. Shrink fit of two cylinders together allows larger operating pressures than a monoblock cylinder, but this is still well below the overstrain pressure. The sketch in Fig. 16 shows a typical high pressure section and its attachment to the pump and launch tube. The connections to the high pressure

section are made far enough uprange and downrange of the maximum pressure region so that the seals do not experience pressures over 100,000 psi, a pressure which can be accommodated by conventional sealing methods. The inside of the high pressure section can be made with a taper which corresponds to the expected expansion at the overstrain pressure, so that after stressing, the inside diameter is almost constant.

It should be noted that the equations for calculating the overstrain pressure assume a constant yield stress throughout the wall and that the elongation of the material has to be sufficient to allow the radial growth. When the wall thickness of a material such as SAE 4340 is over 3 inches, it is difficult to heat-treat uniformly, and a multi-layer construction with some shrink fit between sections is desirable. The shrink fit increases the overstrain pressure only slightly. To allow sufficient elongation and to keep impact strength up, it has been found necessary to keep the hardness of the SAE 4340 or H-11-type materials below a Rockwell "C" hardness of 40. This hardness usually gives a yield strength near 185,000 psi, and with an outside to inside diameter ratio of 5, the maximum operating pressure is 350,000 psi.

In conjunction with the high pressure section, it is necessary to have a piston which will withstand the high pressures encountered during the process. For the relatively light pistons which are employed, two materials have been found which function satisfactorily. Lexan, a polycarbonate, has been used up to 250,000 psi with about one-caliber length necessary for satisfactory operation. Above 250,000 psi, glass-reinforced epoxy has been used up to the maximum pressures which have been achieved. The pistons are made from Scotchply* tape wound with the ply running along the axis and formed in a mold. Lexan is cheaper and cleaner than the epoxy, and it is used whenever possible.

## 6.0 TYPICAL GUN FEATURES

In addition to the $H_2$-$O_2$-He gun which was used for much of the development work, several other guns have been designed and constructed or are under construction. Some of the salient features of three of these guns will be discussed. Figure 17 is an illustration of a 0.625-inch-diameter launch tube, powder-driven gun. This gun was constructed as a model of a larger gun, and a distinct effort was made

*Registered trademark of Minnesota Mining and Manufacturing Company

to keep the cost low while still providing the essential information required for evaluation of the large gun design. In this gun, use was made of commercially available tubing to construct the main segments of the gun, except the high pressure section. The total cost of the gun, including mounts, was below $4000, yet the gun has produced velocities of 26,100 ft/sec with a 2.25-gram projectile and 22,800 ft/sec with a 4-gram projectile. The first stage of this gun was used to obtain the piston velocity measurements given in Fig. 2c.

Because of the large expenditure in time required to keep larger guns operational, some effort has been made to develop simplified operating techniques. The 0.625-inch launcher has been used to develop techniques for efficient launcher operation. It has been found useful to have the pump tube arranged so that it could be easily moved to a cleaning position and equipment (including a drive motor, cleaning brushes, both bristle and wire, and deep-hole hone) available for work on the bore. Frequently, the piston becomes lodged in the high pressure section, and its removal is accomplished by use of a drive motor and a flat-faced bit similar to the type used for drilling wood. When most of the piston is drilled out, the remaining shell of the piston will normally stick to the bit and can be easily extracted. In the event that work on the launch tube involves more than cleaning with a brush and pads, it is quite useful to have a track which can be put in place of the pump tube to carry a drive motor to hone the launch tube in place.

Figure 18 is a sketch of a 2.5-inch-diameter launcher which was designed for use in the 1000-ft hypervelocity range. The gun has a 14.2-inch-diameter chamber, an 8-inch-diameter pump tube, a total length of 96 ft, and is expected to launch a 0.5-lb model at 25,000 ft/sec. The gun is shown with the pump tube moved to the side on its cleaning stand. To enable rapid assembly and disassembly, all large coupling nuts and movements are motorized, and several auxiliary assemblies are being constructed to provide rapid cleaning and routine maintenance. For other than routine work, an 88-ft gun lathe will be located in the same room for work on any of the gun components.

A gun of somewhat different character is shown in Fig. 19. This gun has a 0.5-inch-diameter launch tube and is scheduled to be used as a launcher for impact models. In this launcher the components are constructed rather substantially with the first stage pressure limits near 60,000 psi and maximum high pressure section pressures of 400,000 psi. It is expected that this unit will launch 0.125-in.-diameter aluminum balls near 31,000 ft/sec.

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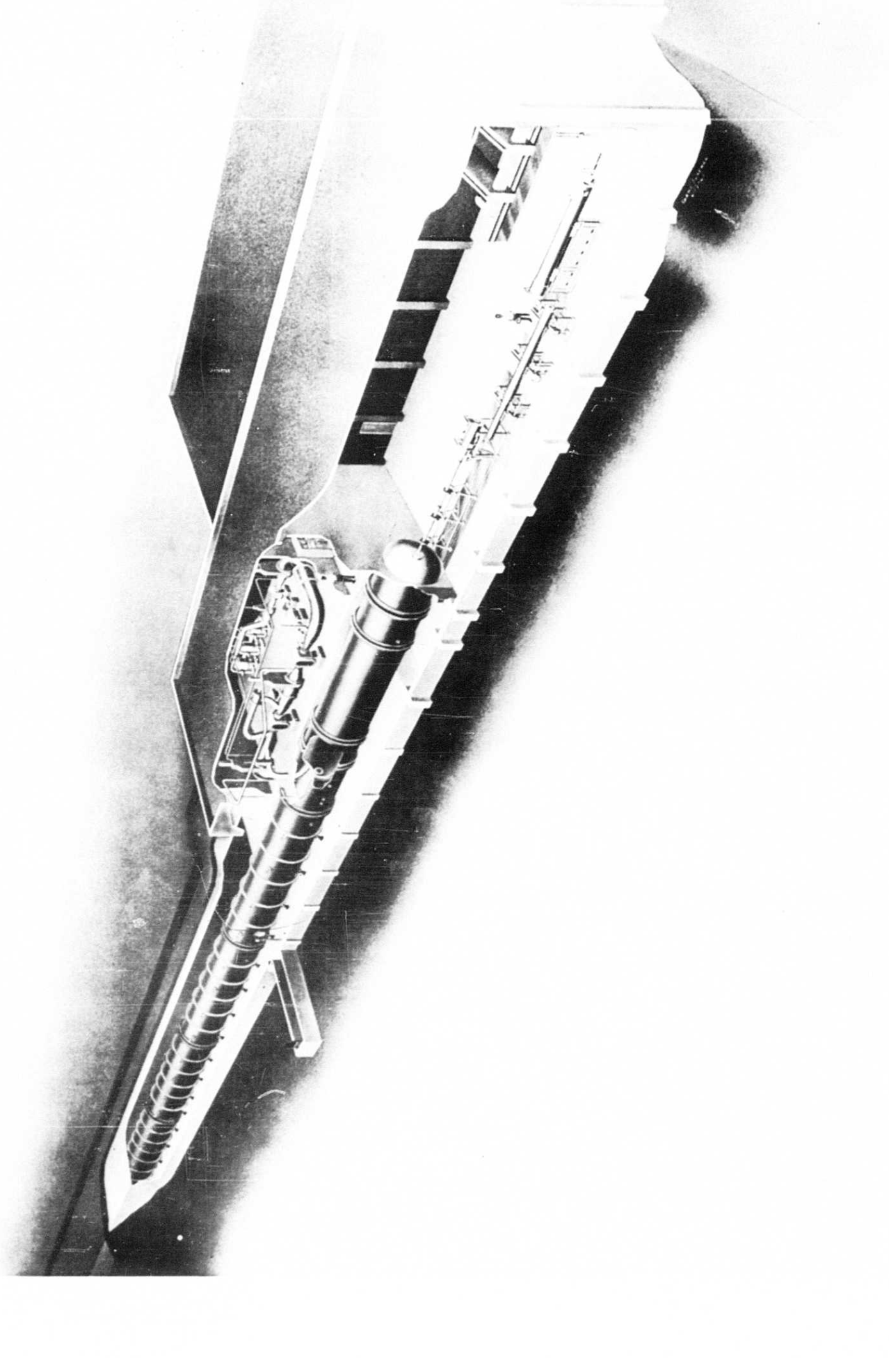
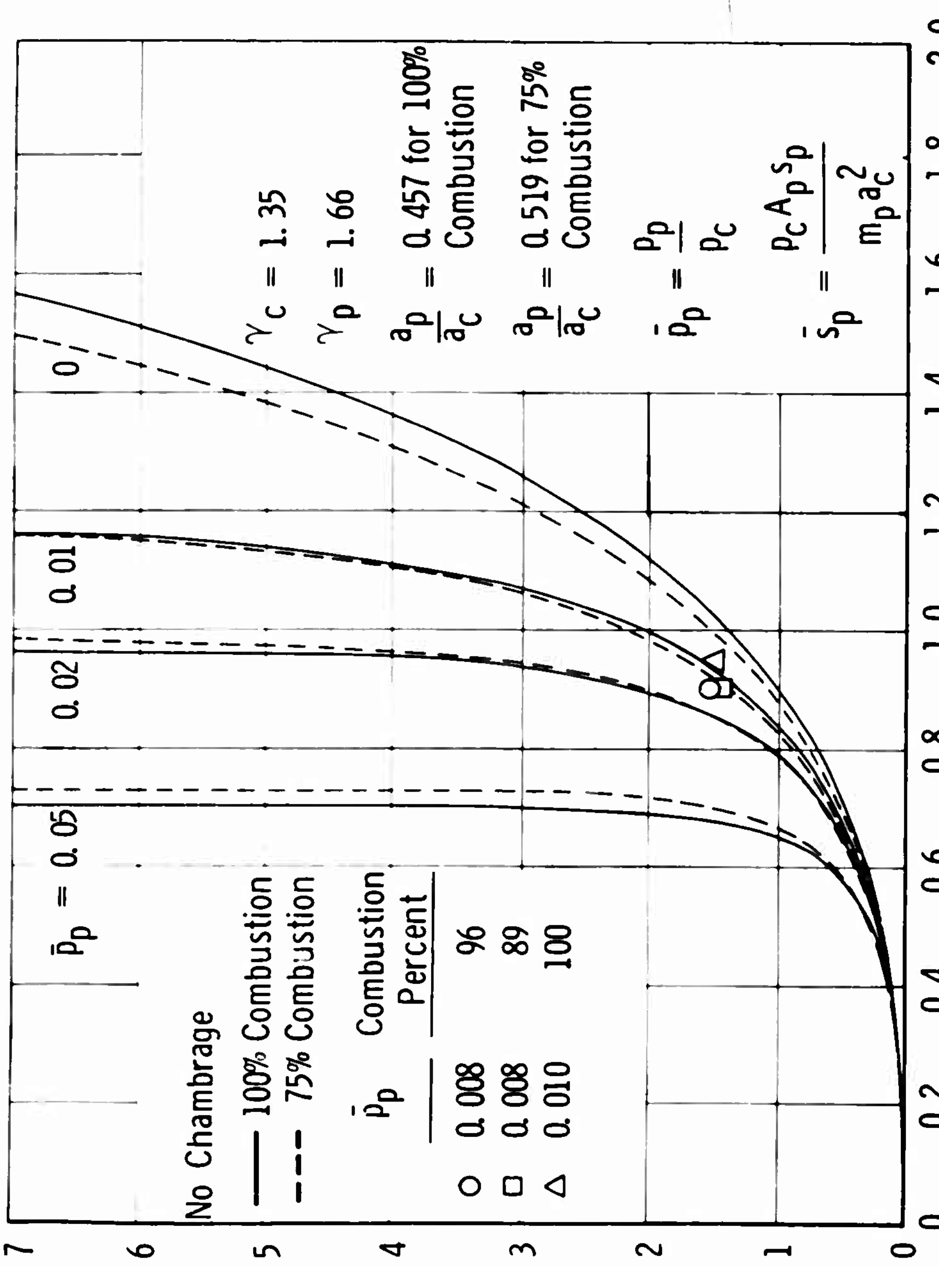
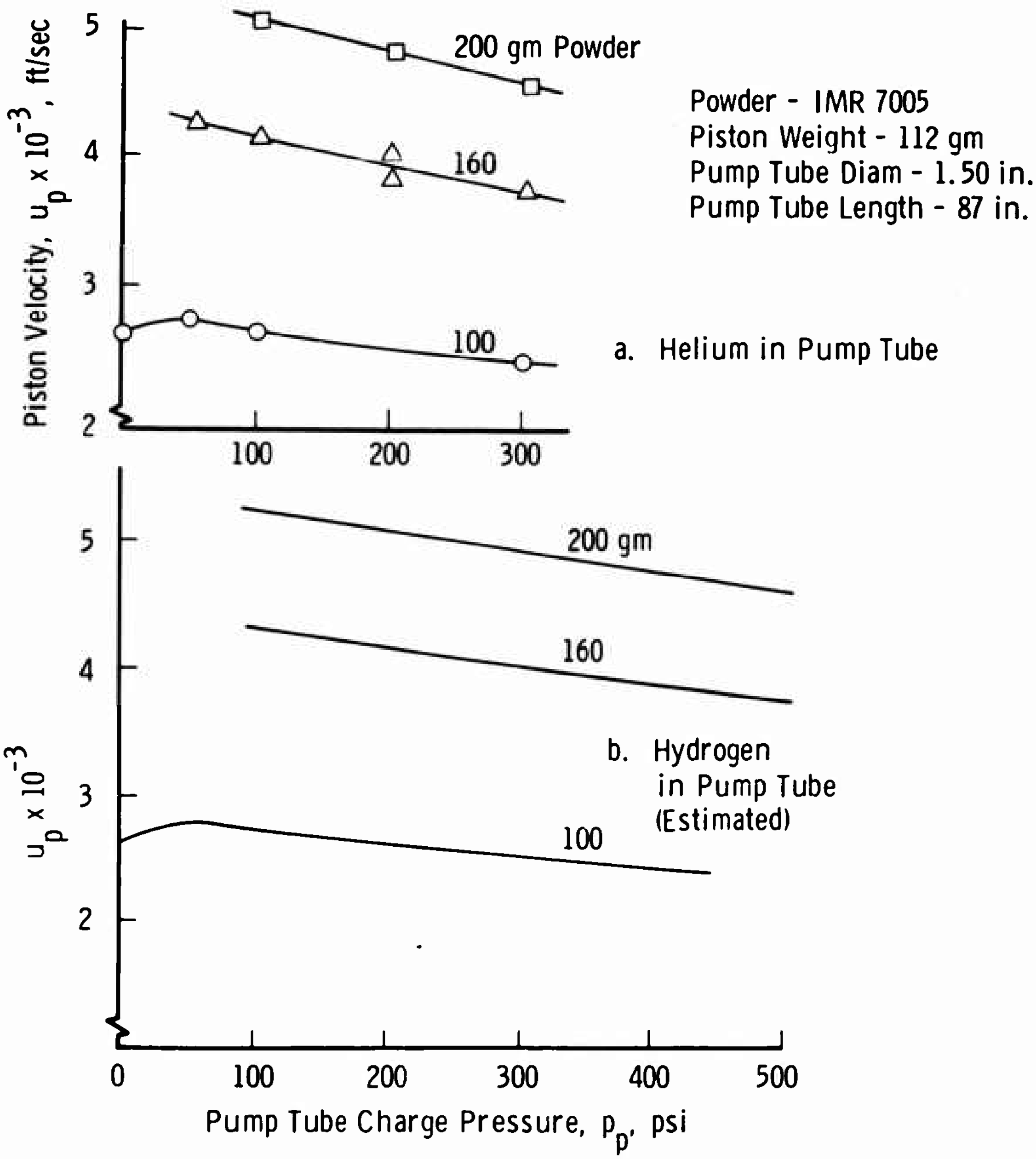


Fig. 1 Future 1000-ft AEDC Range



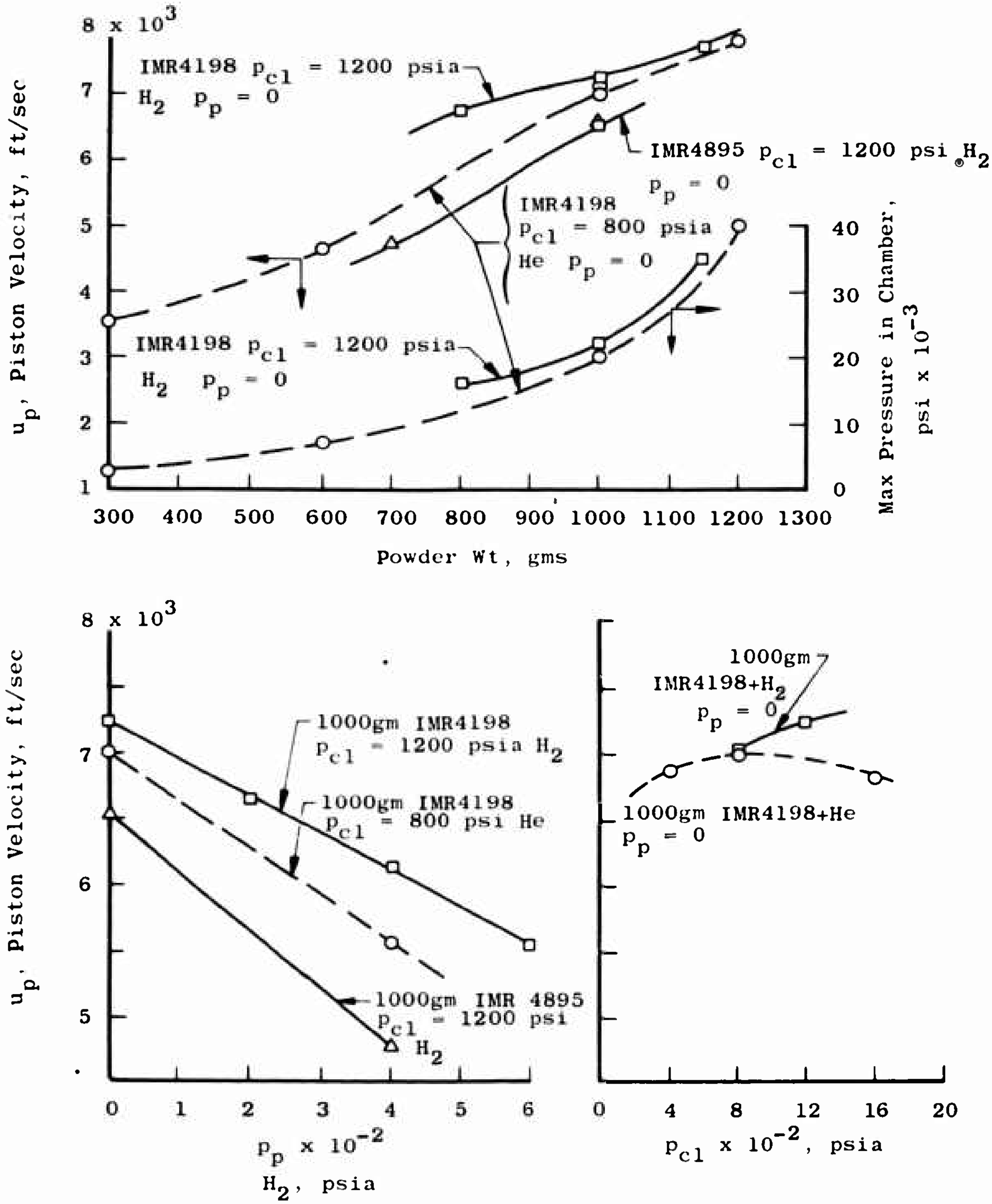

a. $3H_2$-$O_2$-$8He$ Launcher

Fig. 2 Piston Velocity




b. Powder Driver

Fig. 2 Continued




c. Powder Plus Helium or Hydrogen (200-gm Piston, 2.31-in.-Diam and 15.5-ft Pump Tube)

Fig. 2 Concluded

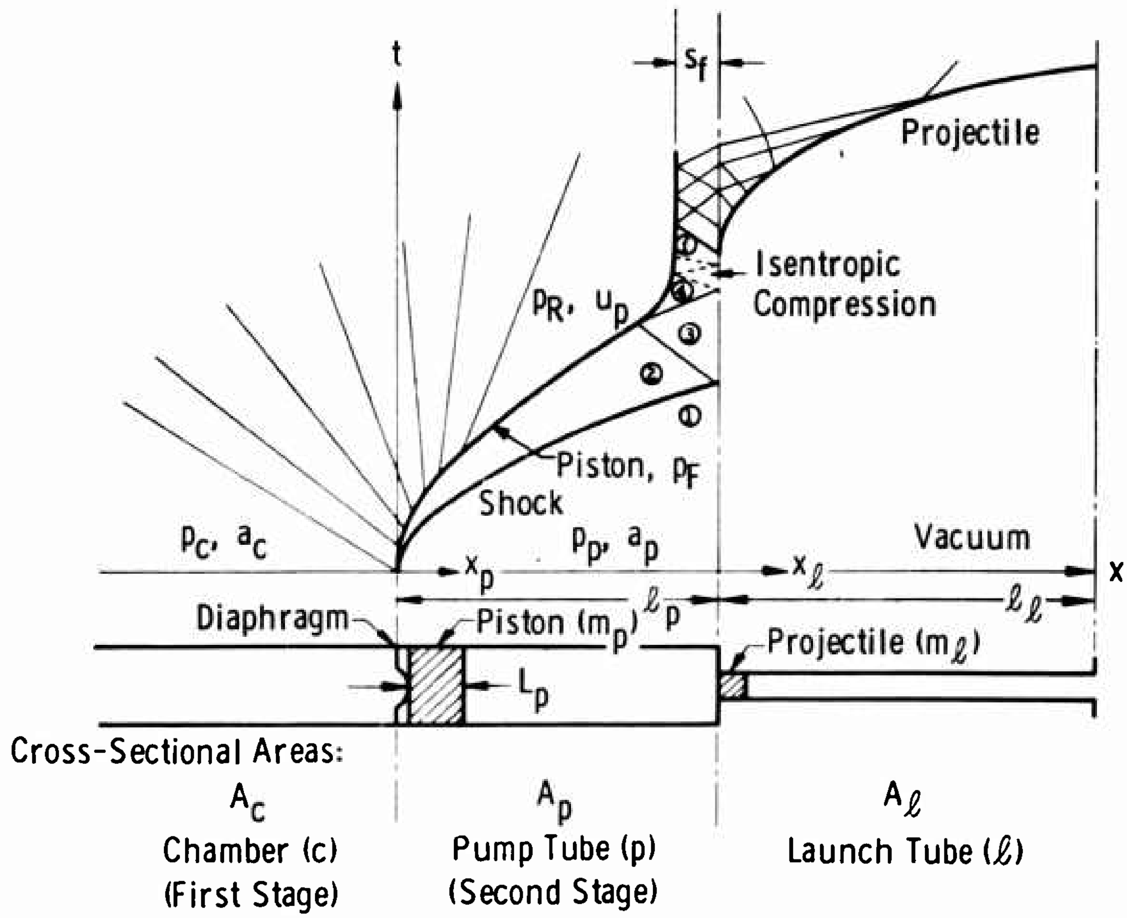



Fig. 3 Wave Diagram of a Two-Stage Launcher

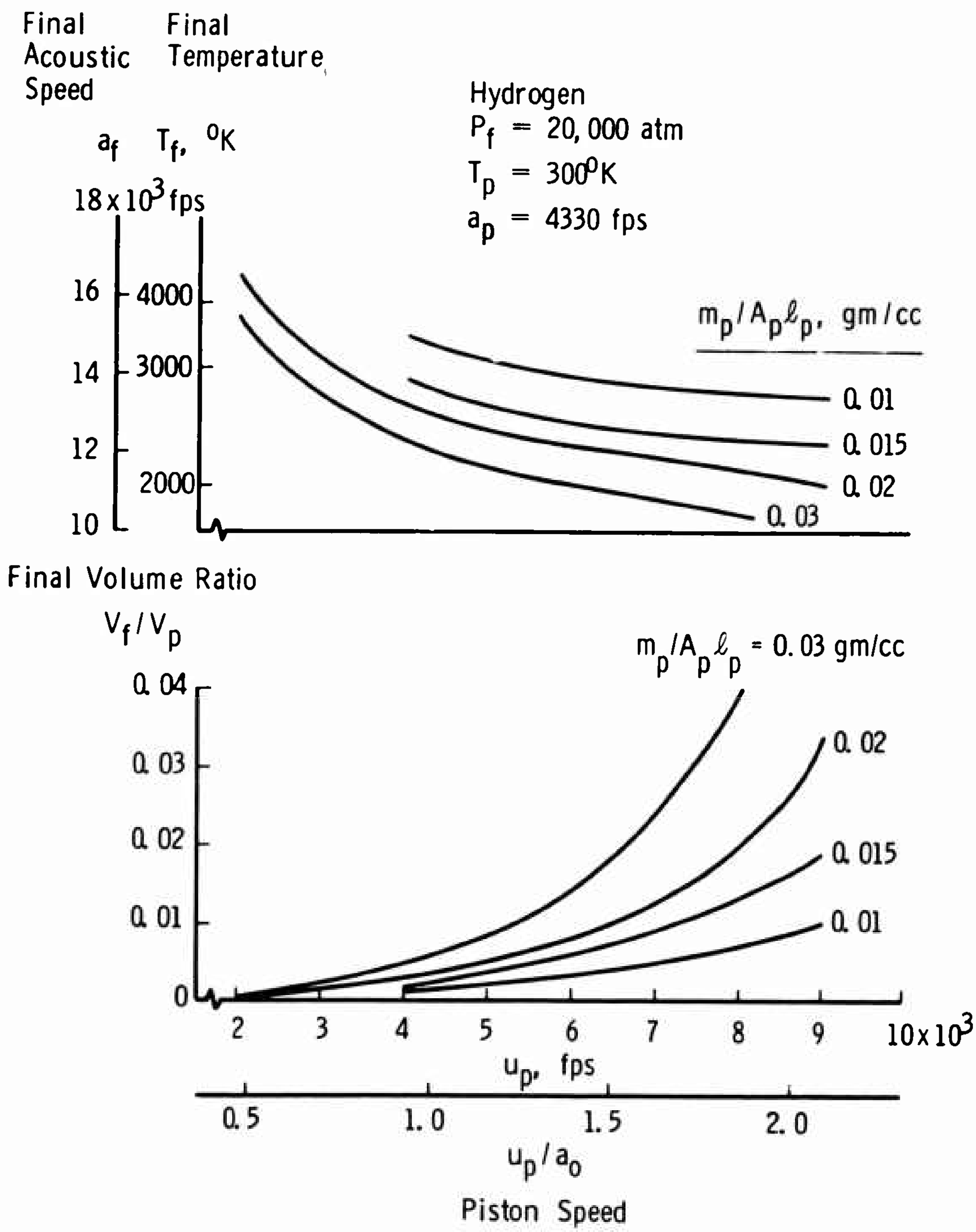



Fig. 4 Final Acoustic Speed and Volume

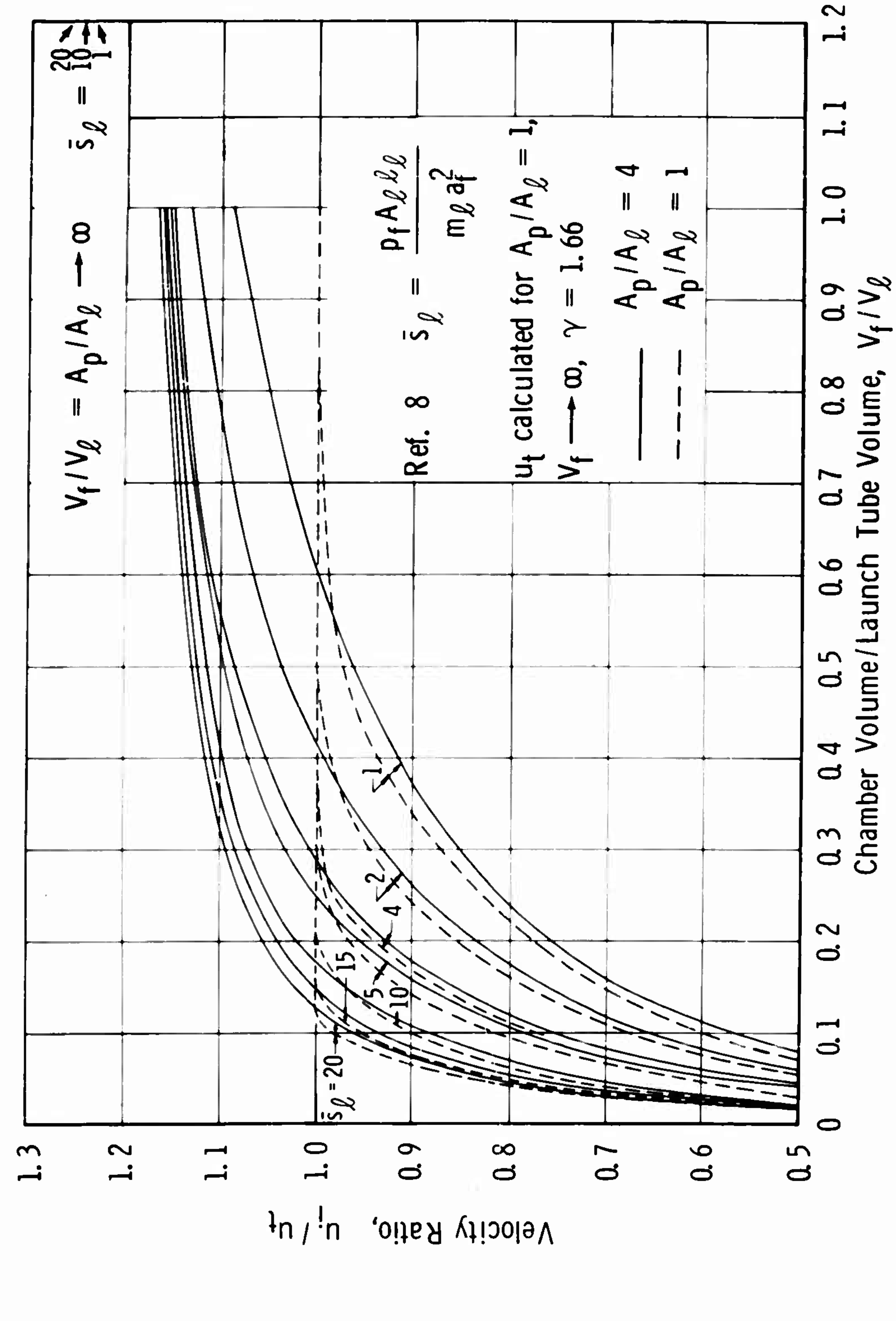
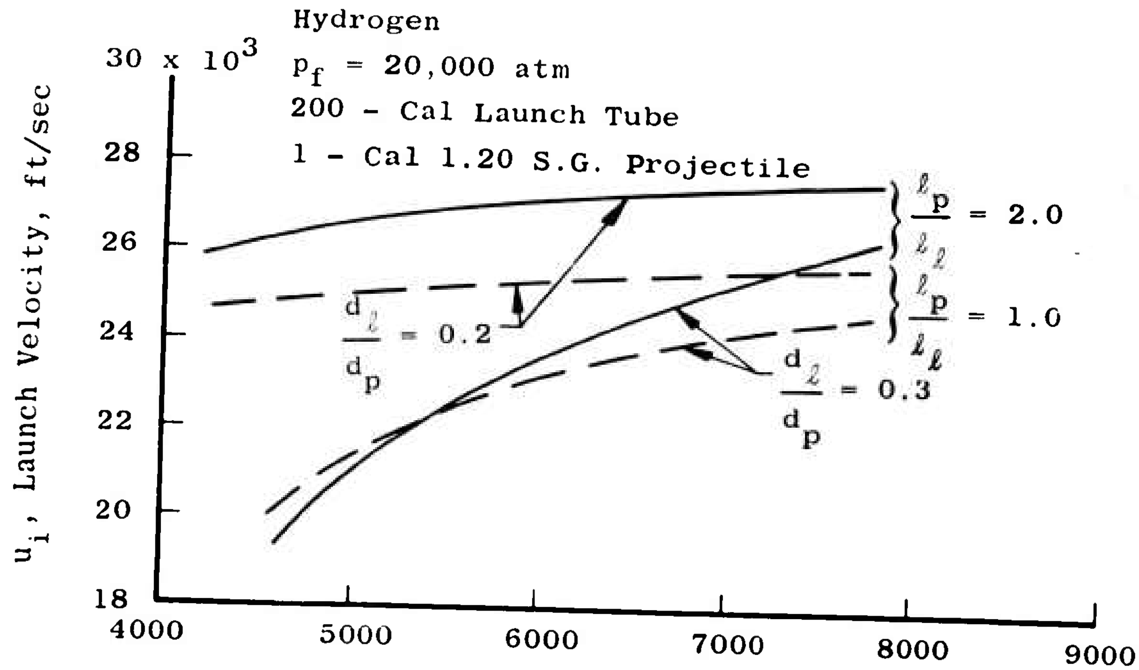
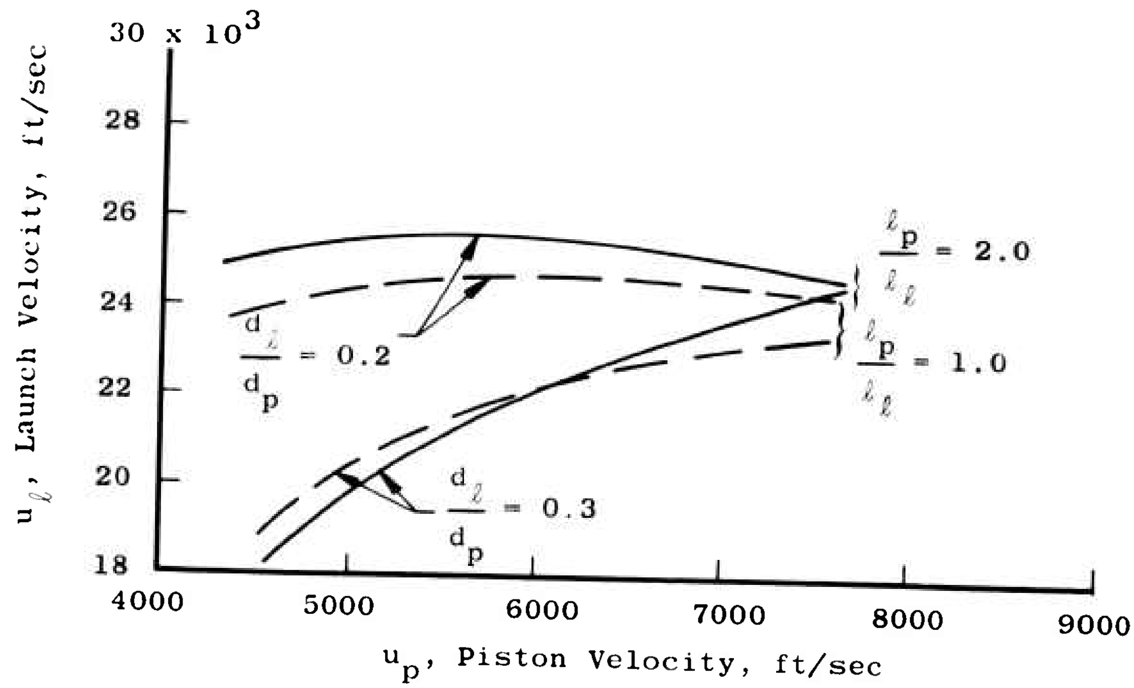



**Fig. 5 Effect of Chamber/Launch Tube Volume Ratio on Launch Velocity**




a. Uncorrected




b. Corrected by Empirical Relation

Fig. 6 Launch Velocities

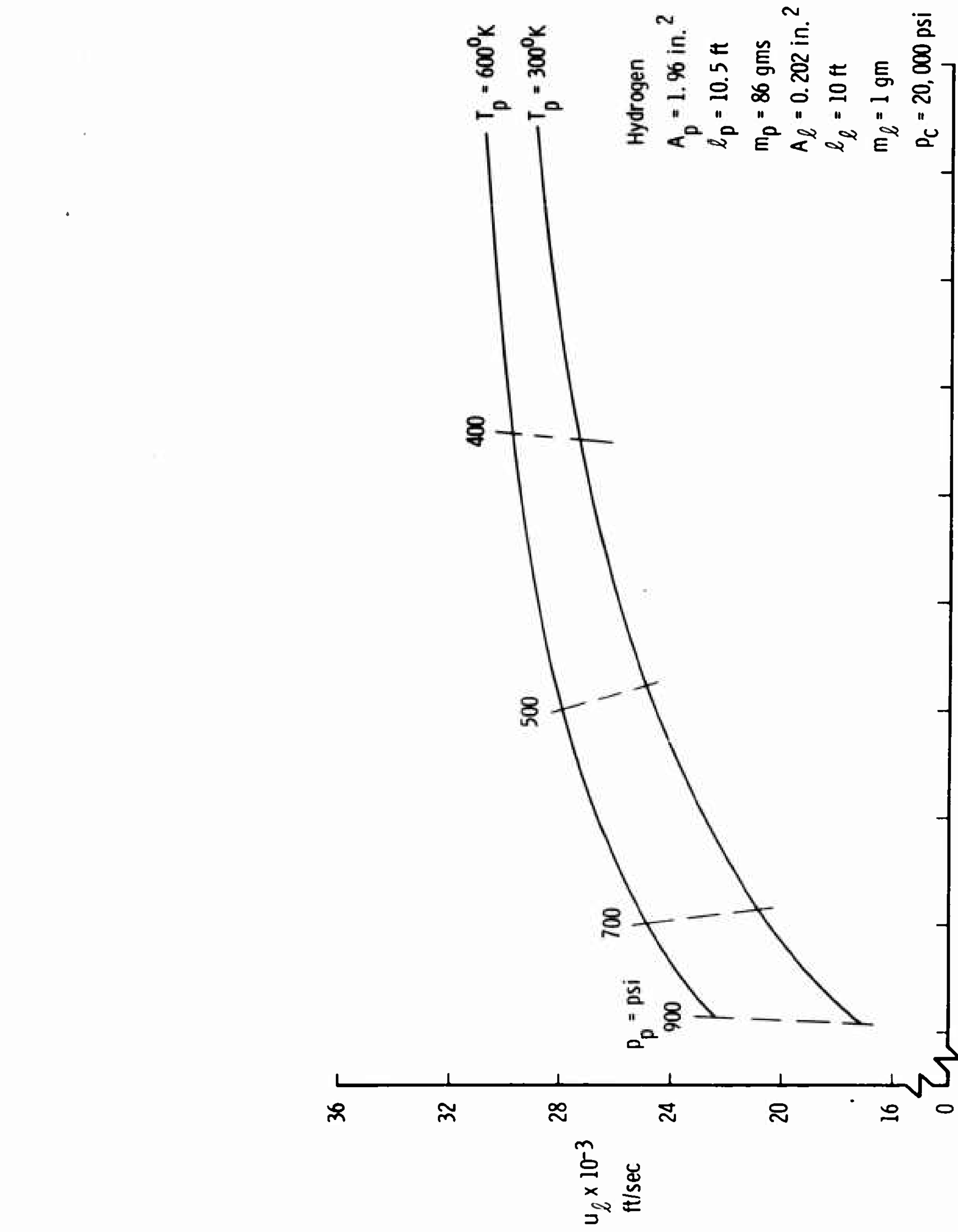



**Fig. 7 Effect of Preheating the Pump Tube Gas**

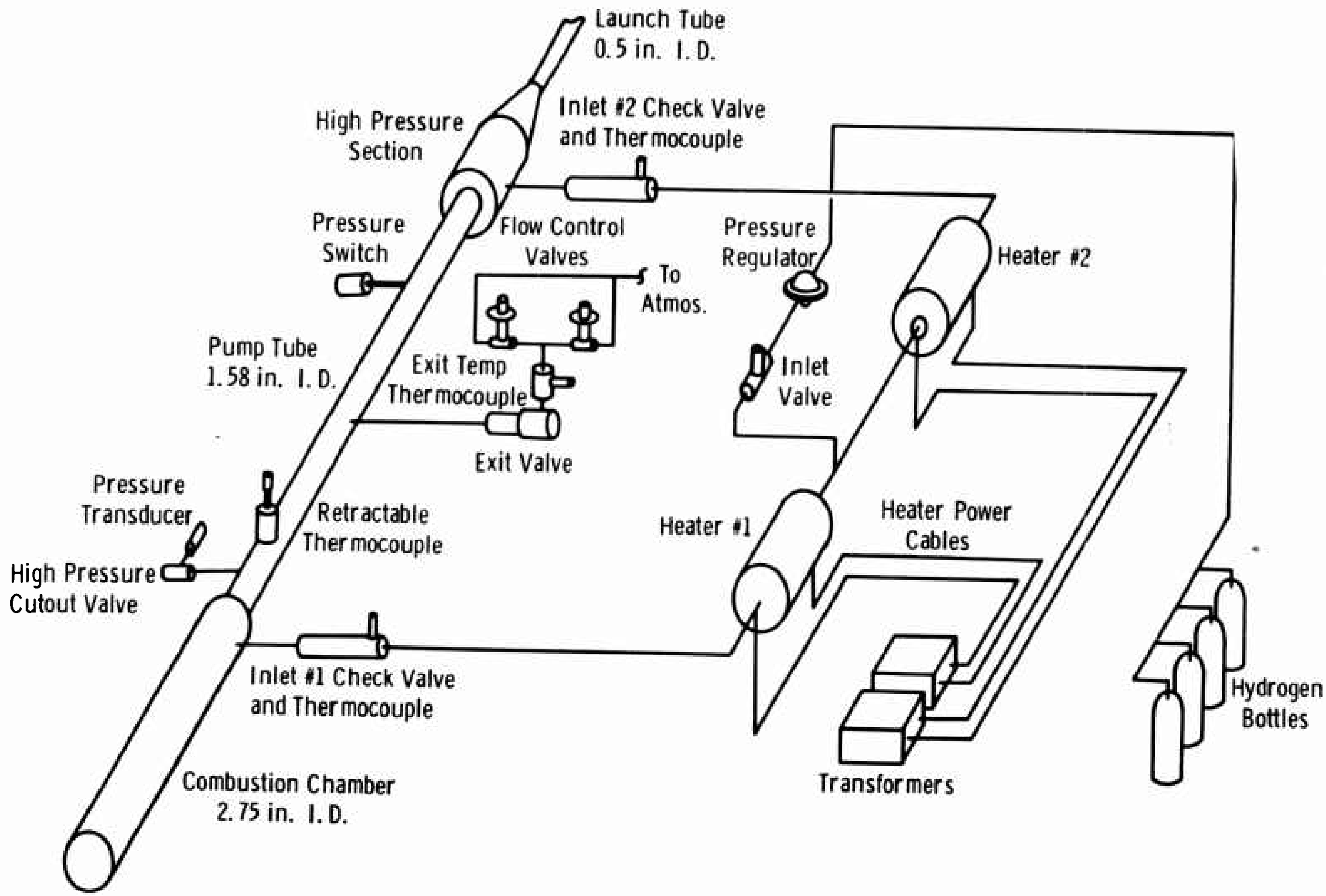



Fig. 8 Pump Tube Gas Heater System (0.5-in.-Diam Two-Stage Launcher)

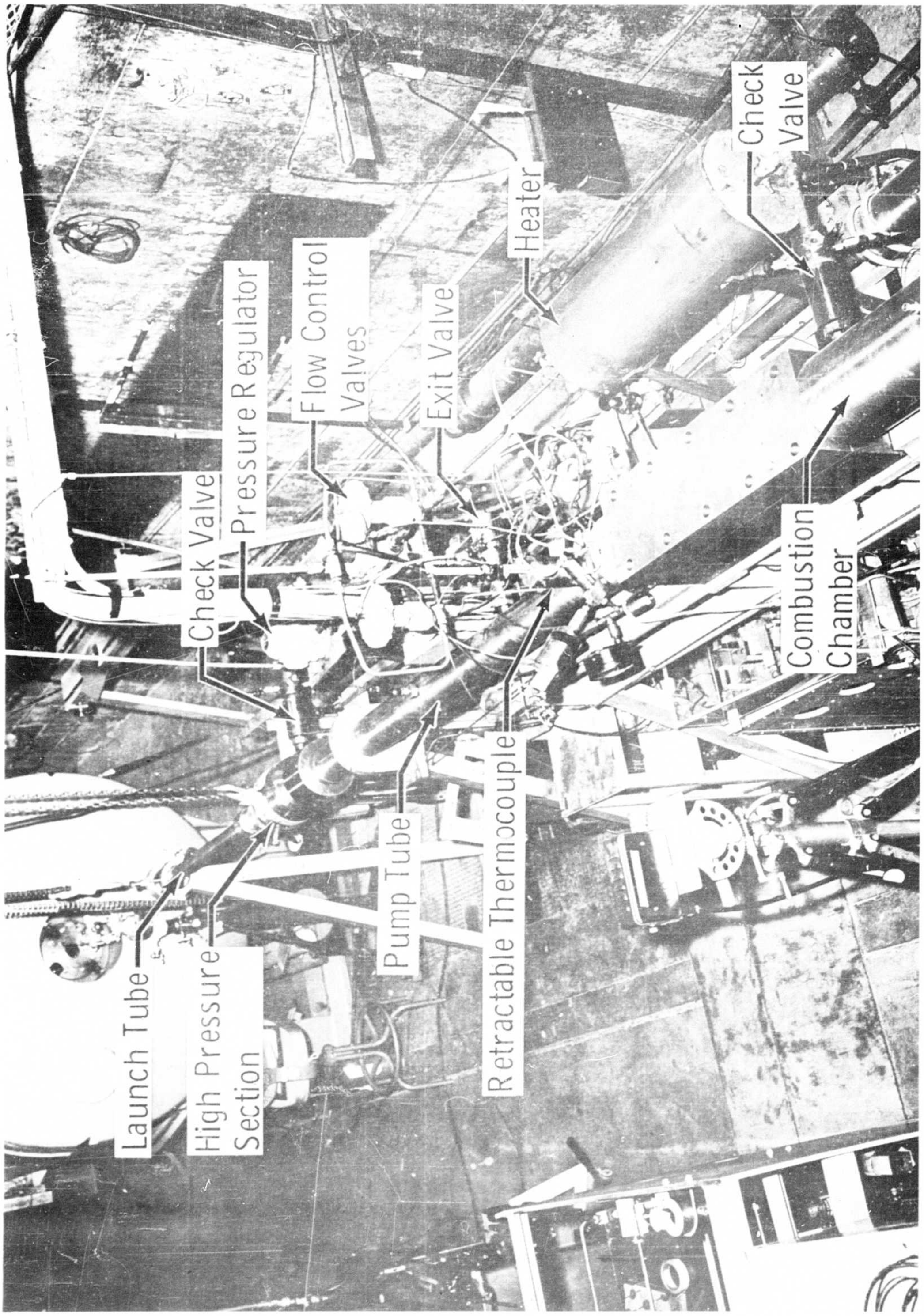



**Fig. 9 Heater Installation**

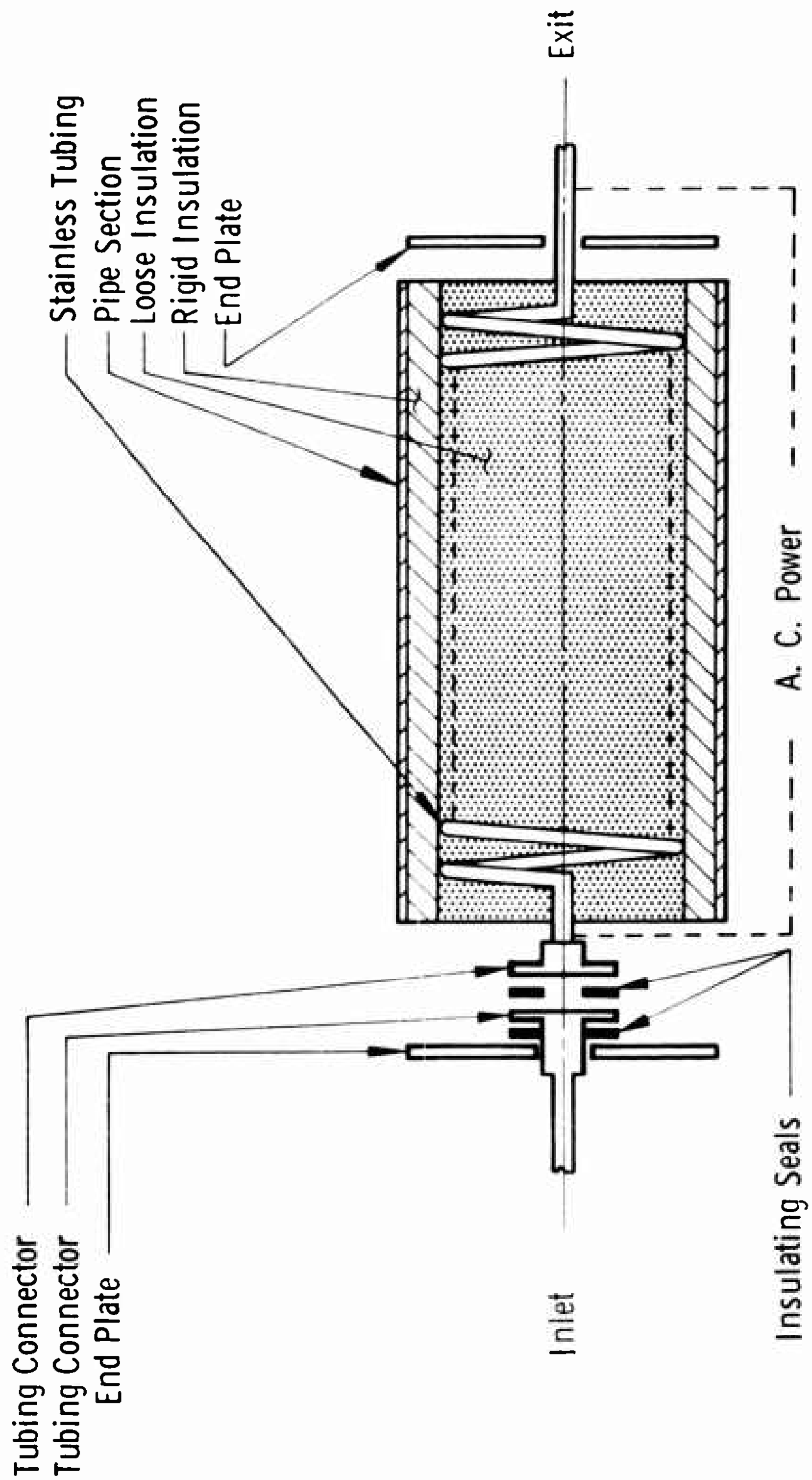



Fig. 10 Gas Heater Components

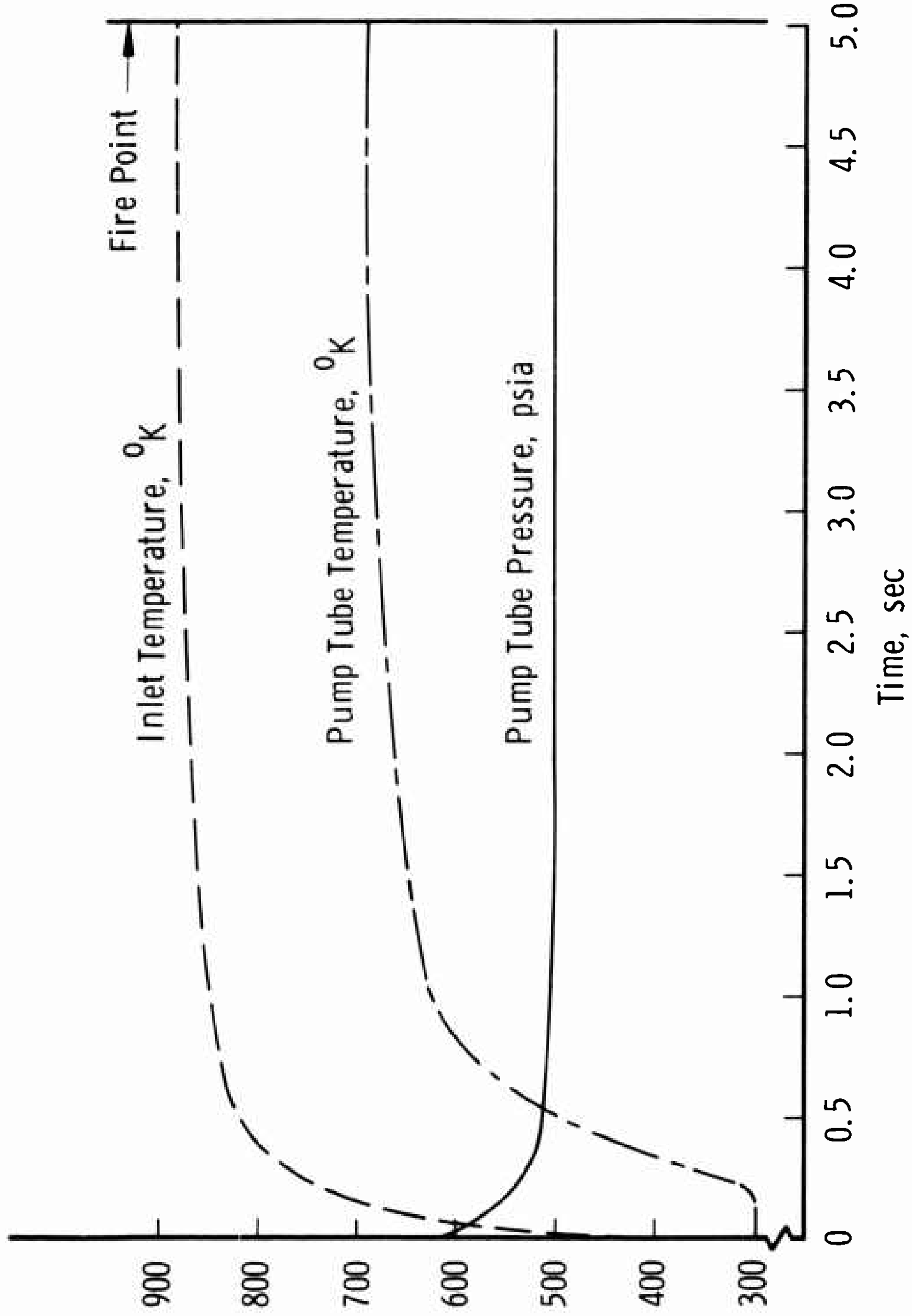



**Fig. 11 Heating System Characteristics**

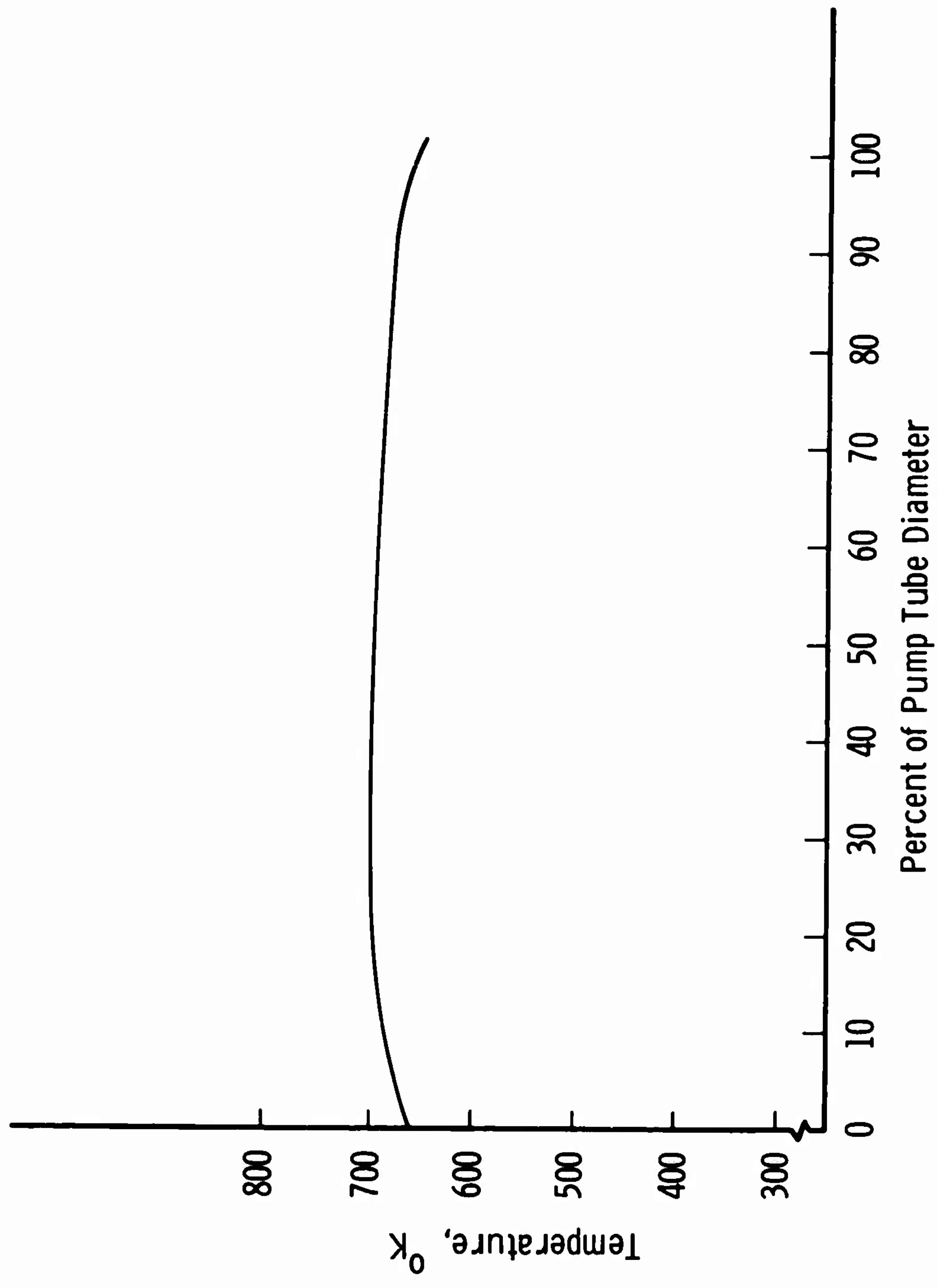



Fig. 12 Pump Tube Temperature Profile

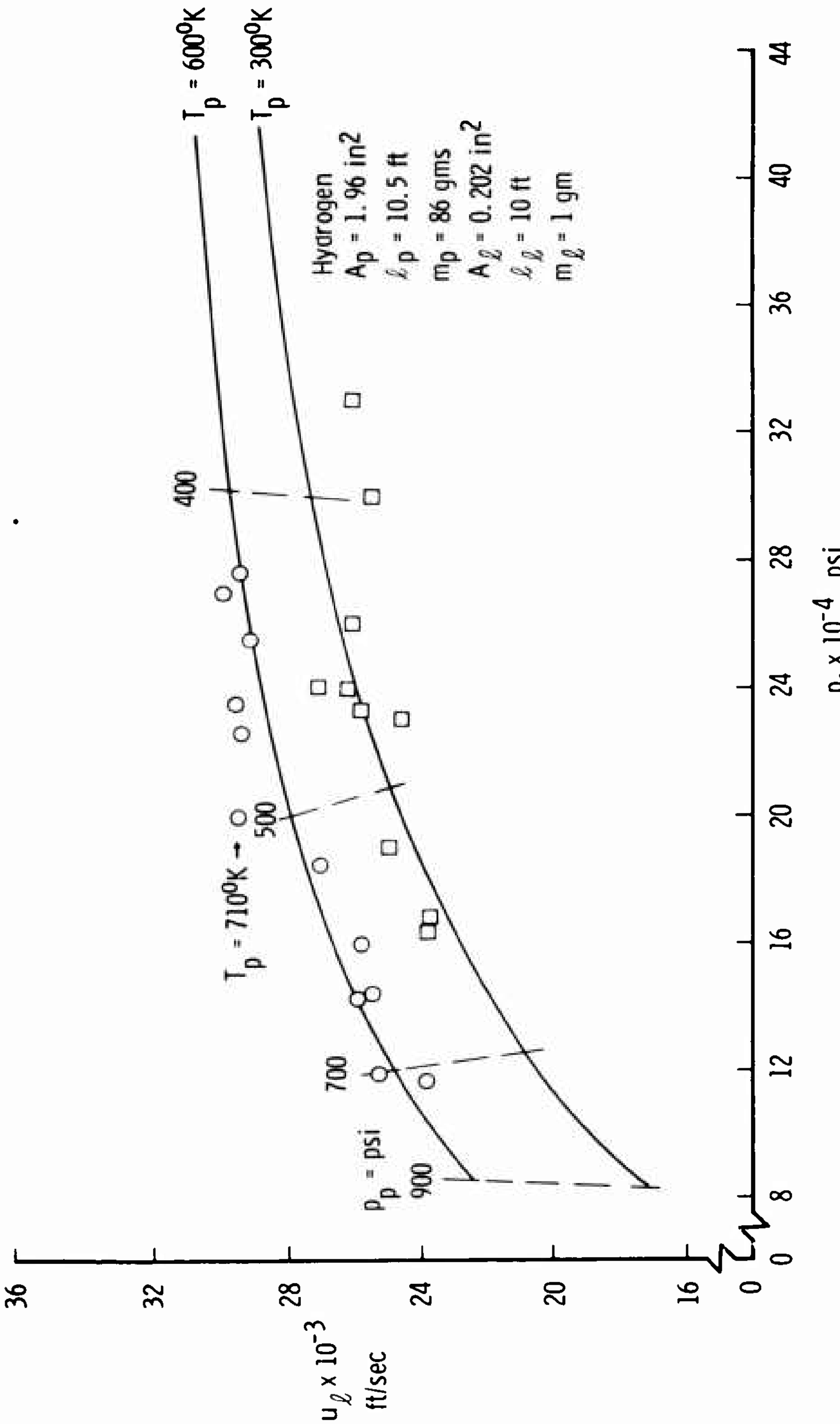



Fig. 13 Launch Velocities Using Heating System

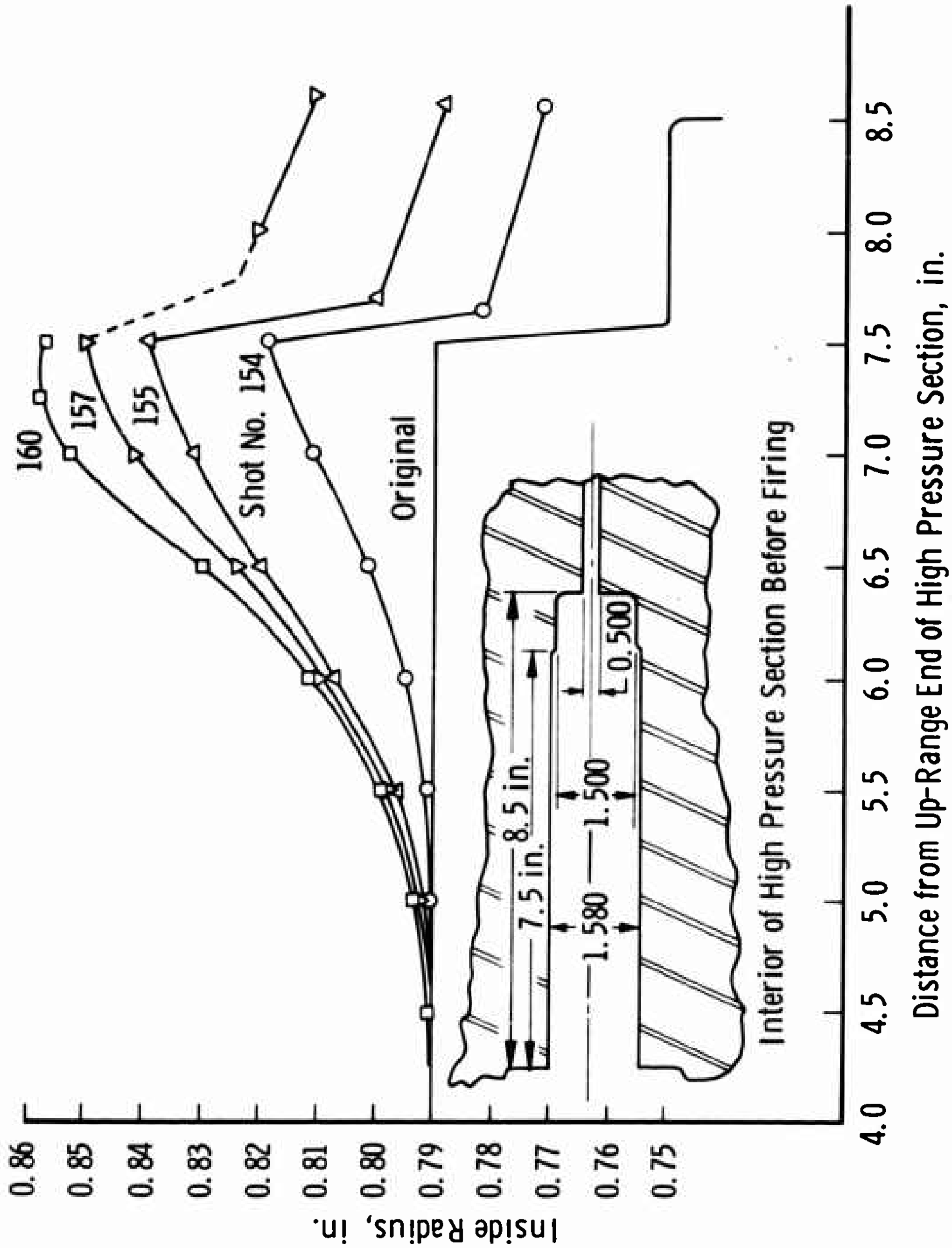



Fig. 14 Growth of the Inside of a High Pressure Section

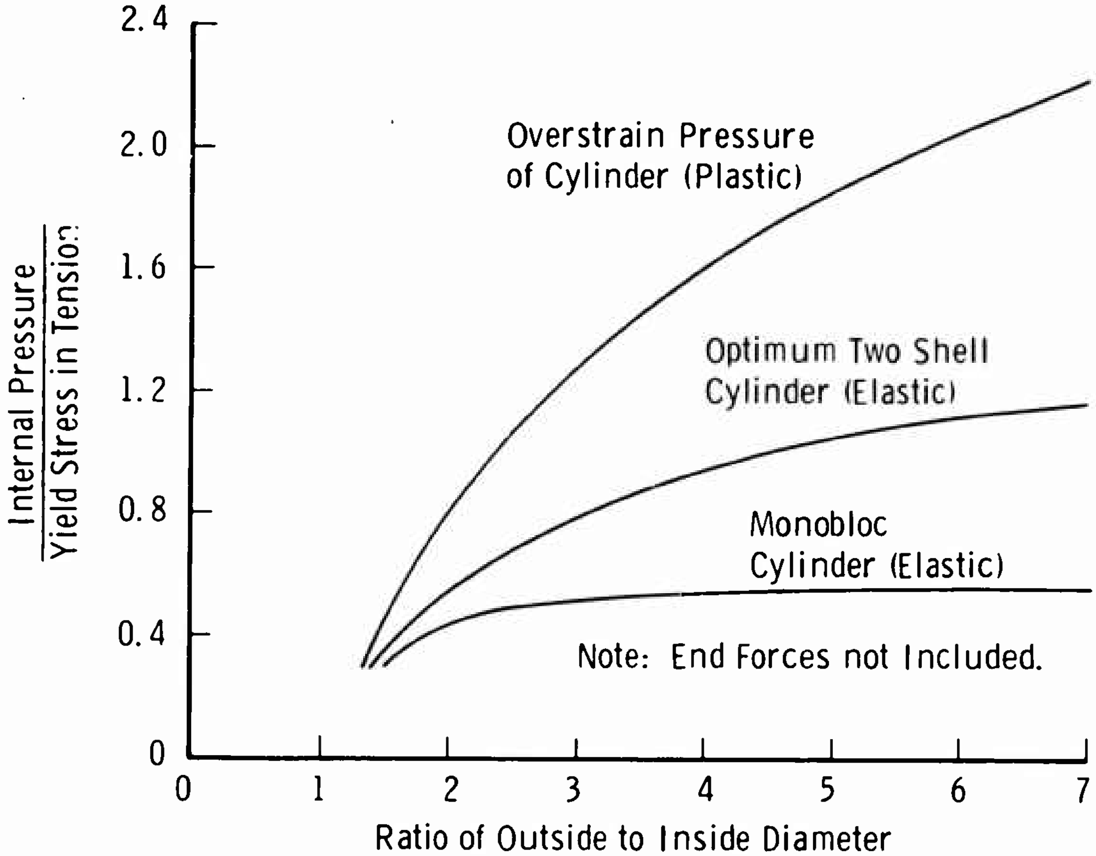



Fig. 15 Comparison of Internal Pressure Capability of Different Construction Methods

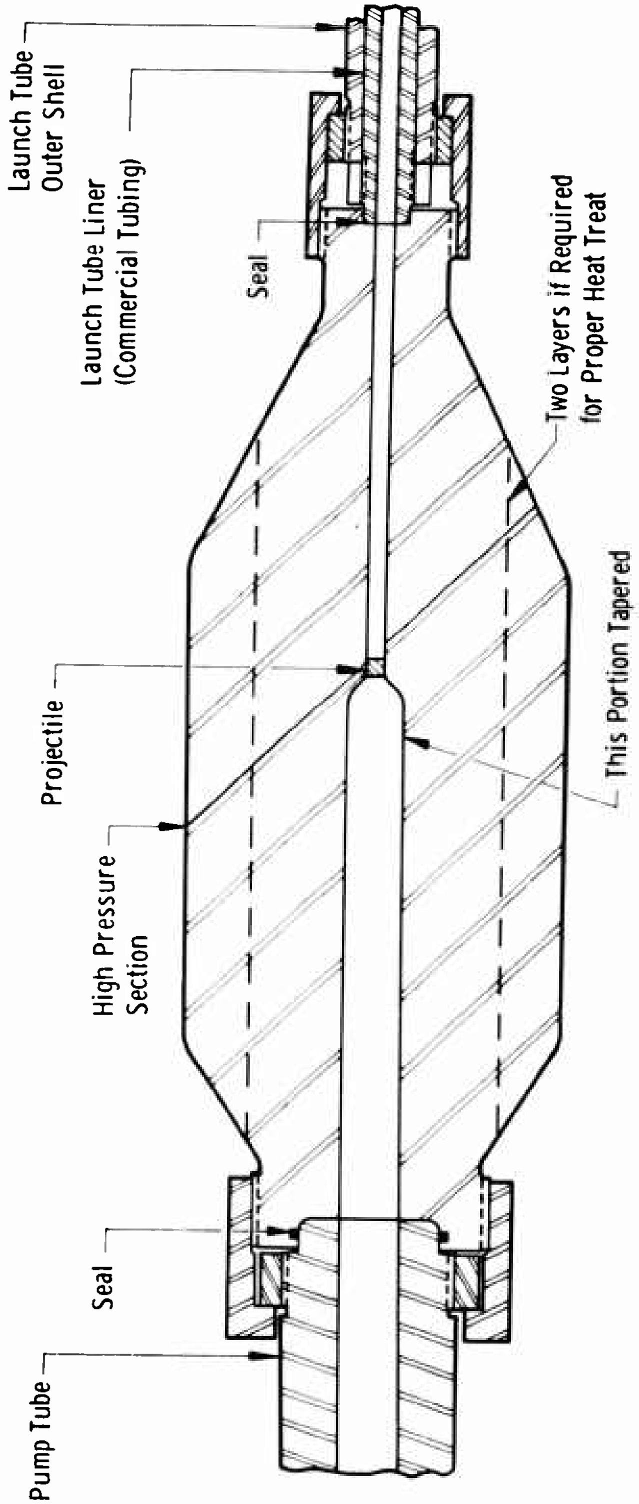



**Fig. 16 High Pressure Region of a Two-Stage Gun**

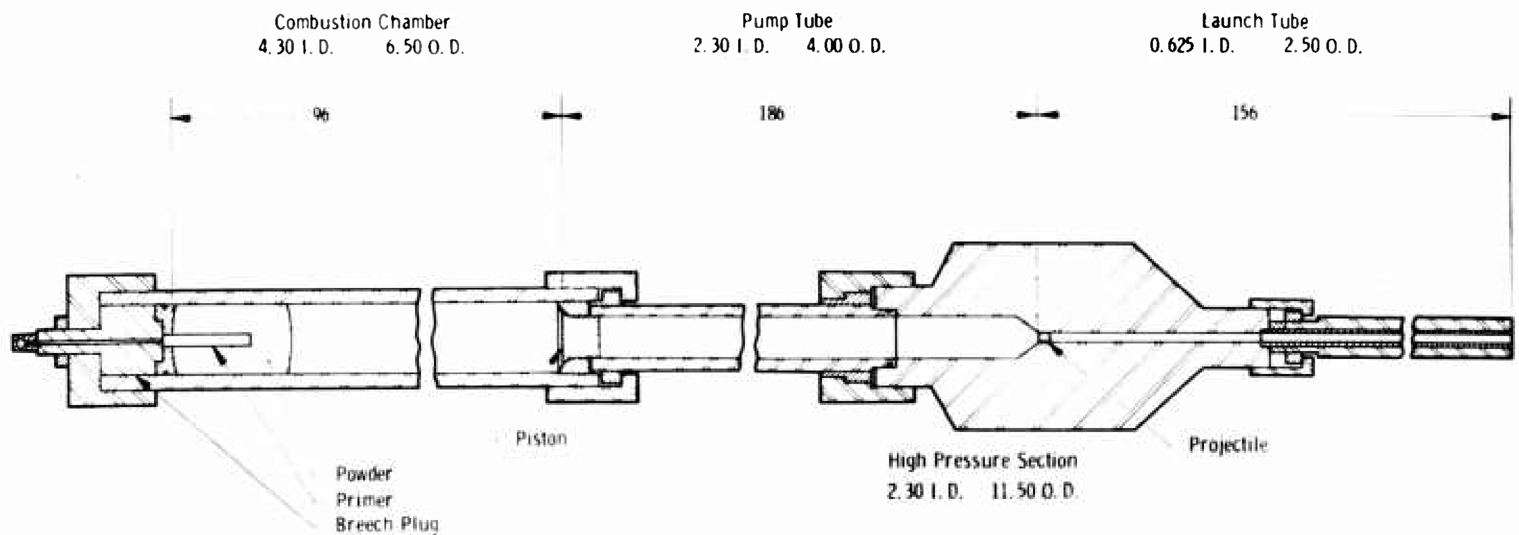



**Fig. 17 0.625-in.-Diam Two-Stage Launcher**

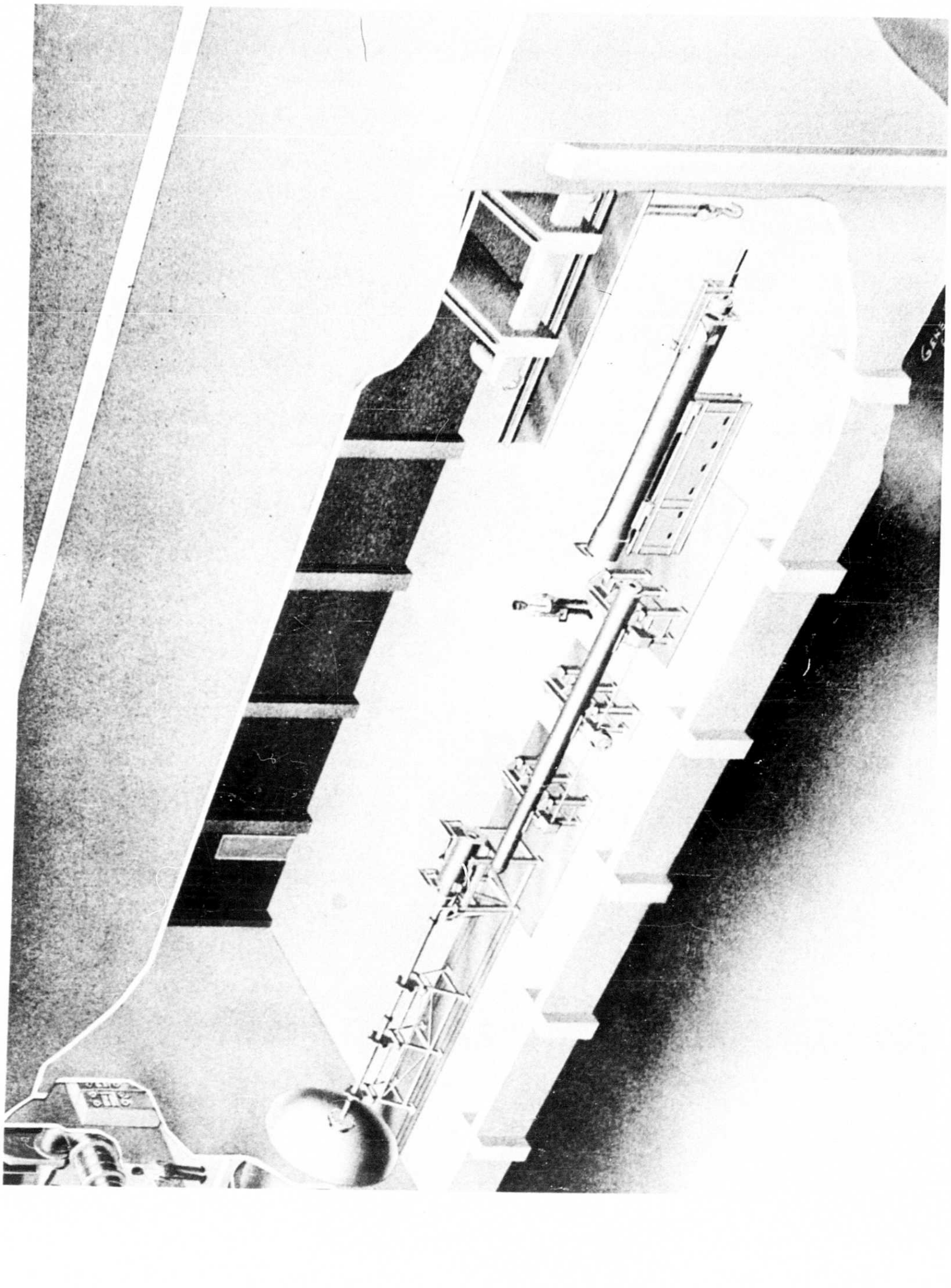


Fig. 18 2.5-in.-Diam Two-Stage Launcher

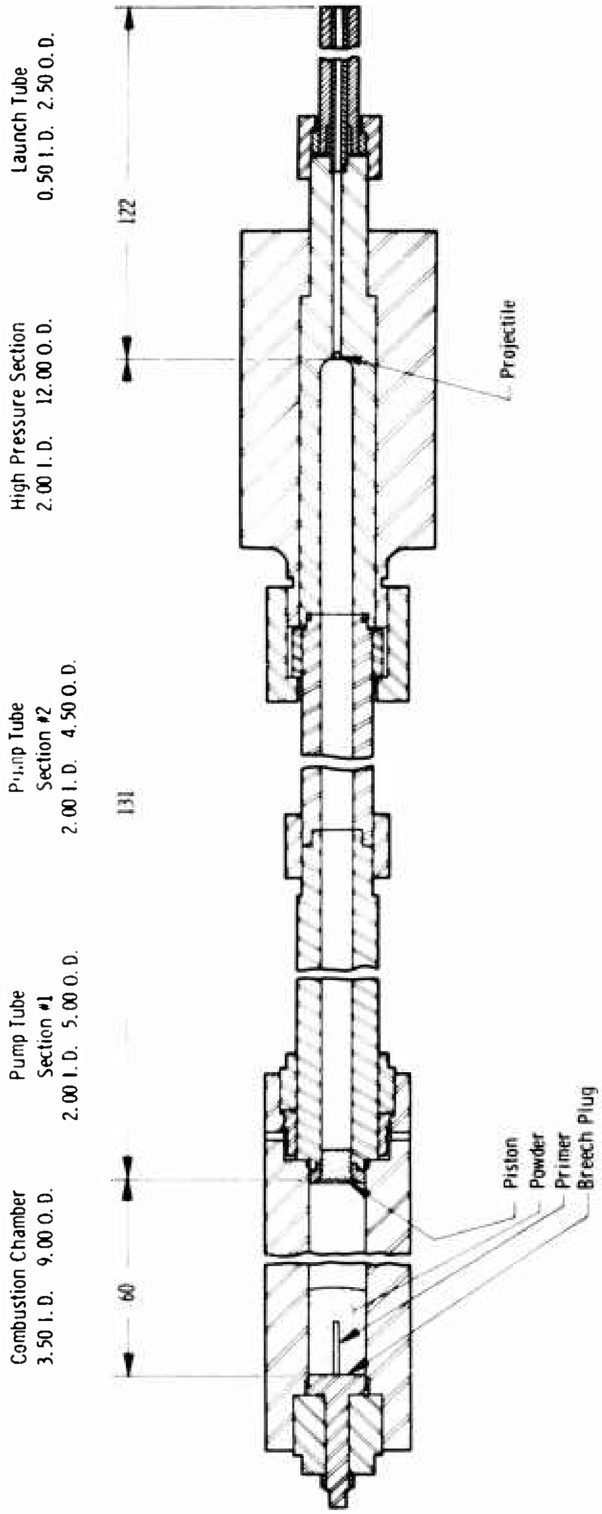



**Fig. 19 0.50-in.-Diam Two-Stage Launcher**

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